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PLASMA CONDITIONS DURING THE GALAXY 15 ANOMALY AND THE POSSIBILITY OF ESD FROM SUBSURFACE CHARGING (POSTPRINT)

Dale Ferguson, et al.

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3550 Aberdeen Ave SE
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Plasma Conditions During the Galaxy 15 Anomaly and the Possibility of ESD from Subsurface Charging

Dale C. Ferguson[1]
Air Force Research Laboratory, Space Vehicles Directorate, Kirtland Air Force Base, New Mexico 87117

William F. Denig
NOAA National Geophysical Data Center, Boulder, Colorado 80305
and

Juan V. Rodriguez
University of Colorado Cooperative Institute for Research in Environmental Sciences, Boulder, Colorado 80309

We review the fundamentals of spacecraft structure, surface and deep-dielectric charging and investigate the environmental conditions and possible spacecraft interactions at the time of the Galaxy 15 anomaly on April 5, 2010. GOES 14 measurements of 30-600 keV electron fluxes associated with an ongoing geomagnetic substorm showed extremely elevated electron temperatures and densities coincidentally peaking near the time when Galaxy 15 exited eclipse. NASCAP-2k is used to model absolute and differential charging effects on a generic satellite similar to Galaxy 15. Tables of electron and proton stopping power are used to calculate deep-dielectric charging from penetrating charged particles prior to the anomaly. Finally, we discuss the possibility that the Galaxy 15 anomaly may have been due to electrostatic discharge (ESD) as a result of surface and/or internal charging and recommend possible design considerations that might mitigate the occurrence of ESD on future spacecraft even under extreme environmental conditions.

Nomenclature

ACE	=	NASA's Advanced Composition Explorer satellite
CME	=	Coronal Mass Ejection from the Sun
ESD	=	Electrostatic Discharge
ESTAR	=	NIST Electron Stopping Power and Range Tables
Faraday cage	=	an enclosure completely surrounded by conducting materials
GEO	=	Geostationary Earth Orbit
Geomagnetic substorm	=	disruption in Earth's inner magnetosphere caused by the impact of intense solar winds
GOES	=	NOAA's Geostationary Operational Environmental Satellites
GPS	=	Global Positioning System
K	=	a measure of magnetic field fluctuations associated with geomagnetic storm conditions
Kp	=	an official global average value of *K*
MAGED	=	Magnetospheric Electron Detector on GOES 13-15
MAGPD	=	Magnetospheric Proton Detector on GOES 13-15
MLI	=	multi-layer insulation
NASCAP-2k	=	NASA/Air Force Spacecraft Charging Analyzer Program
NIST	=	National Institute of Standards and Technology
NOAA	=	National Oceanographic and Atmospheric Administration
NUMIT	=	Numerical Iteration deep dielectric charging code
N_e	=	electron density (cm^{-3})
PSTAR	=	NIST Proton Stopping Power and Range Tables
SCATHA	=	Spacecraft Charging At The High Altitudes, the first scientific spacecraft charging satellite
STEREO	=	NASA's twin Solar Terrestrial Relations Observatory solar satellites
SWPC	=	NOAA's Space Weather Prediction Center
T_e	=	electron temperature (keV or Kelvins)
UV	=	ultraviolet light
V	=	potential with respect to the plasma (volts)
WAAS	=	FAA's Wide Area Augmentation System for precision aircraft landings

[1] Principal Physicist, RVBXR, AIAA Senior Member.

I. Background in Spacecraft Charging

The study of spacecraft charging is a mature discipline, having originated more than 35 years ago. One of the most frequently cited satellite charging design guidelines[1] was published in 1984 and about every two years there is an international Spacecraft Charging Technology Conference[2] which brings together interested spacecraft manufacturers, design engineers and the associated research community. Spacecraft designers, builders and operators are painfully aware that spacecraft can become sufficiently charged in the space environment that they may undergo arcing and suffer more-or-less disastrous effects. There are three main categories of spacecraft charging of general concern: absolute charging (sometimes referred to as structure or frame charging), surface charging (including differential charging) and deep-dielectric charging (sometimes referred to as bulk or internal charging).

Surface Charging and Current Balance

The potential that a spacecraft surface comes to within the natural space plasma environment is the result of a current balance, whereby positive and negative charges incident on a spacecraft are balanced by charges escaping the spacecraft. This equilibrium is established very rapidly due to the high mobility of electrons in space in response to local electric fields. Sources of negative current to spacecraft surfaces are electrons collected from the ambient plasma which are affected by electric or magnetic fields and escaping ions which may be impeded by surface work functions. Sources of positive currents to spacecraft are secondary electrons from ion and electron bombardment, photoemission when in sunlight, ion collection from the ambient plasma (which may be affected by electric or magnetic fields), and electrons emitted (which may be impeded by surface work functions). Dielectric materials maintain a surface current balance locally, whereas conductors maintain current balance wherever they extend. In general, a spacecraft will charge absolutely to maintain the global current balance to all surfaces. Differential charging between adjacent surfaces occurs when they charge to different potentials, resulting in potential gradients (electric fields) and the possibility of electrostatic discharges (ESDs).

In general, a spacecraft will tend to charge to a negative potential in a space plasma environment due to the high thermal mobility of the local electron population compared to the more massive ions at an equivalent temperature. The negative potential acts to repel electrons and negative ions while attracting positively charged ions in the local environment. In the absence of other effects, a spacecraft will tend to charge to a negative potential equal to the temperature of the surrounding electrons[1]. Thus, a spacecraft in a geostationary earth orbit (GEO) environment having an elevated electron temperature of perhaps 10 kilo electron volts (keV) may charge to a -10 kilovolt (kV) potential. Of course, real world scenarios are affected by locally produced secondary electrons and photoemission that may change this charging level significantly, as will the active emission of electrons and ions.

Some of the important surface-material properties affecting spacecraft surface charging are:

a. Conductivity (surface and bulk) - the more conductive a dielectric is the faster its differential charge will bleed off to a local conductor,
b. Dielectric thickness and dielectric constant - the thinner the dielectric and the higher the dielectric constant, the more charge it can store at a given voltage,
c. Secondary electron emission (SEE) - if a material has first and second crossover impact energy points, where the secondary yield exceeds and then falls below one, respectively, and it has a positive potential between these points its potential will trend toward the second crossover point. SEE includes backscattered electrons, and
d. Photoemission - electron emission due to the photoelectric effect tends to drive sunlit surfaces more positive than shadowed surfaces.

One important criterion for charging is the ratio of electron flux in the energy range where the secondary electron emission yield is less than one compared to the energy range where it is greater than one[3]. A shorthand way of expressing this is through the electron temperature. An electron temperature above a certain critical level, say 2 to 4 keV, may be required for charging to occur.

GEO satellites have a time period near the spring and fall equinoxes when they are eclipsed every day by the earth. Many satellite electrical anomalies have happened just after the satellite has come out of eclipse. There are three reasons for this:

a. Charging in eclipse is exacerbated by the cold temperatures (decreasing conductivities[4]) and the lack of photoemission.
b. After eclipse exit, there is heightened differential charging because sunlit surfaces will tend to be partially discharged due to photoemission, and the increasing conductivity may allow charges to adjust more readily in dielectrics, leading sometimes to higher electric fields[5].
c. Cold solar arrays, as when the satellite comes out of eclipse, produce higher string voltages and have lower arcing thresholds[6], and this can lead to an increased incidence of solar array arcing.

When the electric fields from differential charging become large enough, an electrostatic discharge (ESD) may occur. It is usually the differential charging between adjacent surfaces that is important. Satellite manufacturers routinely coat exterior surfaces with conductive materials and ground them to a common reference to minimize the occurrence of differential charging. One place where conductive coatings are sometimes not used is on solar-cell coverglasses, and as result ESDs often occur on or near solar-cell arrays. Laboratory and space experiments have shown that there is typically a voltage threshold for arcing by a satellite solar array in GEO which is dependent on temperature, coverglass thickness and other parameters. For a well-designed array where the cell edges and interconnects are covered with an insulating grouting material the voltage threshold at room temperature may be in excess of -2,000 volts[7]. However, for ungrouted arrays or arrays where the grouting material has been damaged this voltage threshold may be -500 volts or less[8].

Requirements for GEO primary arc prevention (ESD) are contained in NASA-TP-2361, "Design Guidelines for Assessing and Controlling Spacecraft Charging Effects."[1]

Deep Dielectric Charging

Spacecraft in the GEO space environment are sometimes subjected to enhanced fluxes of energetic charged particles. These high-energy particles can become embedded within surface materials of sufficiently low conductivity (that is, dielectrics) resulting in local charge build-up. The resultant electric fields will, if unabated, eventually become sufficiently intense to produce a rapid electrostatic discharge (ESD) resulting in high currents and possible damage to spacecraft materials and electronics. Very energetic particles will embed themselves deep inside exposed dielectric materials and/or may pass through exterior shielding materials causing charge deposition and the potential for ESD deep within the spacecraft. Bulk or internal charging of this nature requires high fluences of charged particles having energies of (typically) 200 keV or more.

Important materials properties for deep dielectric charging are:

a. Amount of shielding - oftentimes, dielectrics are hidden behind aluminum or other shielding materials to block entry of high energy particles,
b. Bulk conductivity - when bulk conductivities are very low, charges may linger for days, weeks, months or possibly years[4] continually building up charge until a discharge occurs,
c. Breakdown voltage threshold - materials with low breakdown thresholds are more prone to deep-dielectric discharge at lower doses of buried charge than materials with high breakdown thresholds,
d. Dielectric constant - materials with high dielectric constant can store more charge before a breakdown occurs, and
e. Presence or absence of a surface conductor - conductors can concentrate electric fields and can more readily induce a discharge.

Many important spacecraft failures are believed to have been due to deep-dielectric discharge, including the Anik E-1 and 2 satellites and the NOZOMI Mars spacecraft, the latter of which was impacted by energetic particles during a solar storm[9]. An empirical criterion (rule of thumb) for a spacecraft deep-dielectric discharge is an accumulated charge of 10^{10}-10^{11} electrons per cm^2 over a 10-hour period[10].

Several computer codes are available to the spacecraft charging community to model spacecraft charging potentials. An American industry standard code for determining surface potentials on spacecraft surfaces is the NASA / Air Force Spacecraft Charging Analyzer Program (NASCAP-2k) which is available to U.S. citizens through the NASA Space Environment Effects (SEE) program[11]. In Section III we describe the results of a spacecraft charging simulation using NASCAP-2k to assess a possible charging response of the Galaxy 15 GEO satellite to the space environmental conditions at the time of the spacecraft anomaly which occurred on April 5, 2010. Other modeling tools available to the spacecraft charging community are the Numerical Integration (NUMIT) dielectric charging code[12] and National Institute of Standards and Technology (NIST) codes[13], ESTAR and PSTAR, for estimating penetration depths in spacecraft materials from high energy electrons and protons, respectively. ESTAR and PSTAR were also used in this assessment.

II. What is Galaxy 15 and Why is it Important?

Galaxy 15 (Figure 1) is a GEO communications satellite built by Orbital Sciences Corporation (OSC) and operated by Intelsat. The satellite, launched in 2005, was on-orbit for about 4.5 years before the occurrence of a spacecraft anomaly on April 5, 2010, that effectively ended its useful life. Galaxy 15 used the STAR™ Bus GEO communications platform which was advertised by OSC to be essentially immune to spacecraft charging[14]. One distinct feature of Galaxy 15 compared to other satellites using the STAR Bus design was the presence of L-band antennas on the earthward pointing face (and its associated electronics) used by the Federal Aviation Administration for the Wide Area Augmentation System (WAAS). Galaxy 15 was parked over the 133^{o} W GEO station and was primarily used to relay DirecTV signals to millions of customers within North America.

The electronics systems for satellites using the STAR Bus designs are advertised to be inside a Faraday cage.[15] Satellite surfaces, except perhaps for the L-band antennas in the case of Galaxy 15, are apparently covered with conductive black Kapton® multi-layer insulation (MLI) in accordance with satellite design recommendations provided in NASA-TP-2361. In contrast, the solar cell coverglasses in the STAR Bus design apparently have no grounded conductive coatings[16], in violation of one of NASA-TP-2361 key recommendations. These design features are considered in the spacecraft charging model discussed later in this paper.

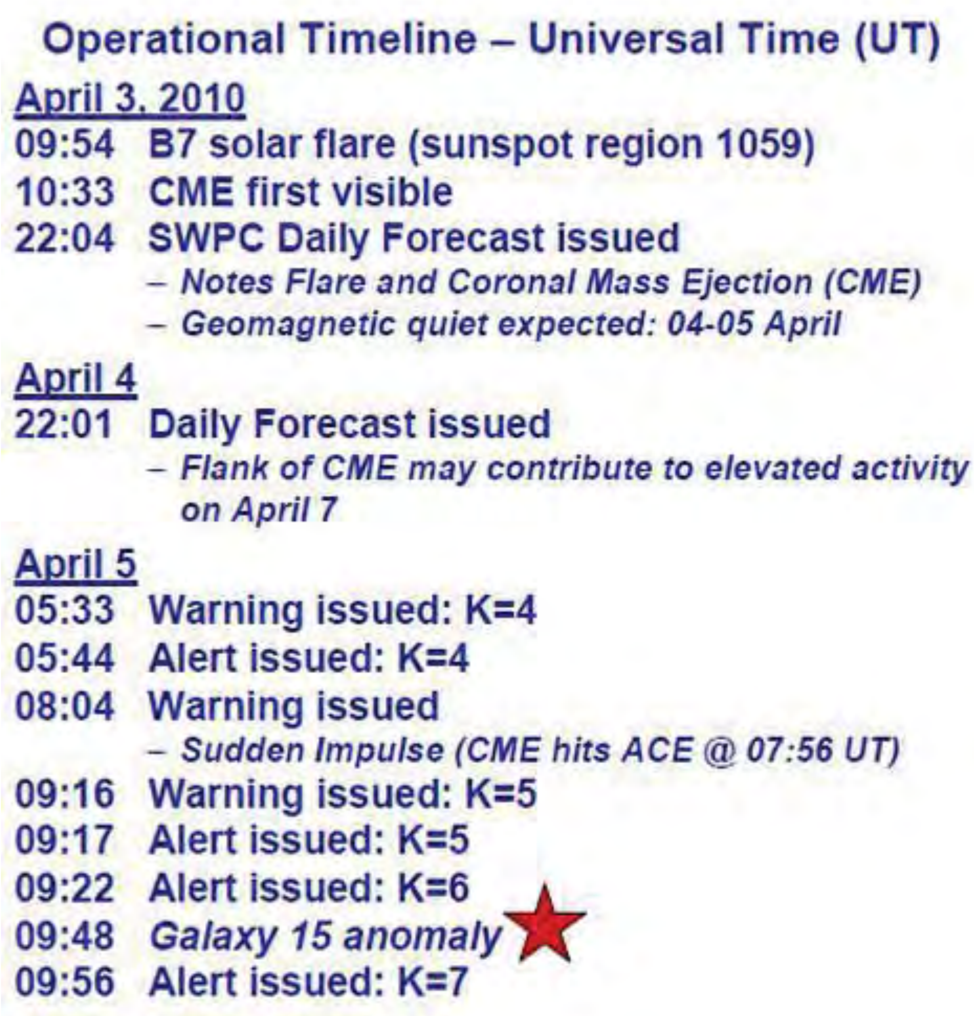
Fig. 1. The Galaxy 15 satellite before launch.

The Anomaly

On April 5, 2010 the Galaxy 15 satellite experienced a spacecraft anomaly at 09:48 UT when the spacecraft suddenly and unexpectedly stopped responding to ground commands. The anomaly apparently did not affect other satellite systems as the satellite continued to relay back to ground any broadcast signals it received, maintain attitude control and broadcast GPS signal data for the WAAS. However, since Galaxy 15 was no longer responding to station-keeping commands it started to drift in longitude out of its designated slot region and risked interfering with the operations of neighboring communications satellites. As of 29 November 2010 the Galaxy 15 satellite continues to function autonomously and drift unabated thereby forcing other GEO communications satellite operators to conduct interference avoidance maneuvers. It is expected that at some point over the next month or so Galaxy 15 will lose sun-lock, after which the batteries are expected to drain and the spacecraft will then cease to function. However, a similar expectation for September 2010 did not occur. Following the loss of the Galaxy 15 satellite its mission was assumed in large degree by the older Galaxy 12 on-orbit spare.

Timeline of the Anomaly

The timeline below[17] refers to the documented events that preceded the Galaxy 15 spacecraft anomaly on April 5, 2010:



The sequence of events that may have led to the Galaxy 15 failure was initiated by a solar flare eruption on April 3, 2010 that was observed by the x-ray sensor on the NOAA Geostationary Operational Environmental Satellite (GOES 14). Shortly thereafter the NASA Solar and Heliospheric Observatory (SOHO) and Solar TERrestrial RElations Observatory (STEREO) satellites detected a coronal mass ejection (CME) plasma cloud ejected from the solar surface and tracked the motion of the CME through interplanetary space on its earthward trajectory. These events were monitored by solar forecasters at the NOAA Space Weather Prediction Center (SWPC) in Boulder, Colorado, who, over the next two days, issued a series of warnings and alerts of increasing concern. The geo-effective CME was detected at 07:56 UT on April 5 by the NASA Advanced Composition Explorer (ACE) satellite located close to the earth near the L1 Lagrangian point[18] at approximately 240 earth radii in the sunward direction. Space particle and field measurements at L1 provide solar forecasters with a 30 to 45-minute advanced warning of possibly disruptive "space weather" conditions.

When the CME reached earth it caused the terrestrial magnetosphere to be reconfigured and resulted in a geomagnetic storm of surprising intensity. The storm period included a number of geomagnetic substorms, the first of which was particularly intense[23] with a *Kp* index of 7+. This substorm was detected by the space particle and field monitors on the GOES 11-15 satellites located in the post midnight-to-early morning sector in close proximity to Galaxy 15. Of particular relevance to this discussion is the fact that this substorm occurred at about 09:00 UT while the Galaxy 15 satellite was eclipsed by the earth. The debilitating anomaly occurred at 09:48 UT shortly after Galaxy 15 had come out of eclipse at 09:20 UT. The closest GOES satellite to Galaxy 15 was GOES 11 (135^o W), which, unfortunately, had no capability for measuring the electron energy spectrum below 600 keV. However, GOES 14, located ~1.9 hours later in local time (104.5^o W), included a new-generation Energetic Particle Sensor (EPS) with a capability for measuring energetic electrons in the energy ranges from 30 to 600 keV (the MAGnetospheric Electron Detector [MAGED]) and protons from 80-800 keV (the MAGnetospheric Proton Detector [MAGPD]).The MAGED consisted of nine telescopes at different pitch angles, each with five energy channels (30-50, 50-100, 100-200, 200-350 and 350-600 keV)[26]. A particle pitch angle refers to the angle between the local magnetic field and the velocity vector for a measured charged particle distribution. Similarly, the MAGPD consisted of nine telescopes and five channels although at different energies (80-110, 110-170, 170-250, 250-350 and 350-800 keV).[26]

Number densities and temperatures for the GOES 30-600 keV electrons and 80-800 keV protons were estimated using a methodology based on the Los Alamos National Laboratory (LANL) moments calculations[27], with changes to account for the different instruments and the presence of a magnetometer on GOES. First, the pitch angle for each telescope was determined using the magnetic field components from a co-manifested triaxial fluxgate magnetometer[26]. The velocity distributions (i.e., the number of particles per unit volume in configuration space per unit volume in velocity space) were then calculated as functions of pitch angle and energy. The number density was calculated as the zeroth -order moment integral of the velocity distributions over pitch angle and velocity, whereas the temperature components parallel and perpendicular to the local magnetic field were calculated from the second-order moment (energy) integral. The average temperature of the distribution was calculated from the equipartition theorem as two-thirds of the perpendicular temperature plus one-third of the parallel temperature.

The electron densities and temperatures derived from the velocity moments of the 30-600 keV fluxes measured by GOES 14 revealed that:

a. The electron temperature measured by GOES-14 reached a maximum of about 86.4 keV (~10^9 K!) at about 09:14:30 UT (about 5½ minutes before the nearby Galaxy 15 satellite exited eclipse). This extraordinarily high temperature was more than seven times the NASA "worst-case" electron environment used in the standard NASCAP-2k simulations and leads us to believe that Galaxy 15 may have experienced an extreme level of absolute charging while still in eclipse. GOES electron flux measurements in the energy range 30 to 600 keV were quite well fit (R^2 = 0.96-0.98) by a single Maxwellian distribution, and the electron temperatures parallel and perpendicular to the local magnetic field were approximately equal until after the anomaly, indicating that the electron distribution was almost isotropic. Electron temperatures from GOES 14 moment calculations are shown in Figure 2.

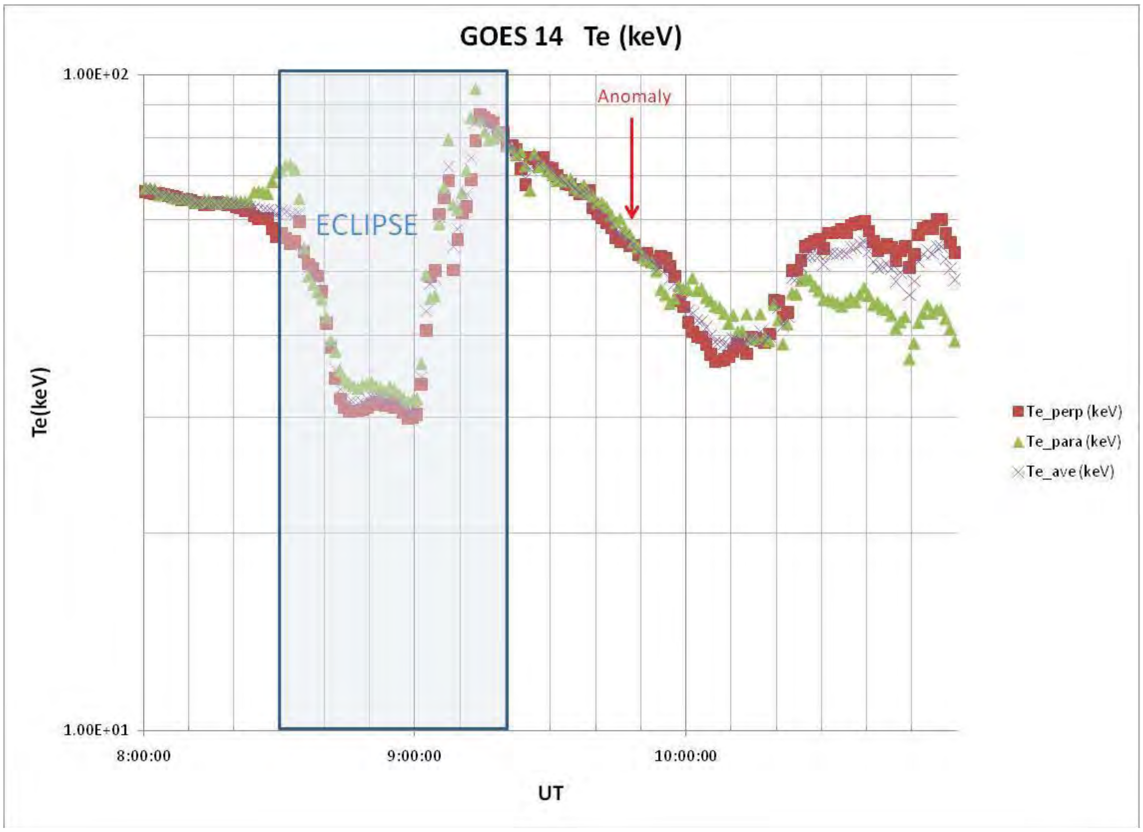


Figure 2. GOES 14 30-600 keV electron temperature moments near the time of the anomaly. Eclipse times shown are for Galaxy 15.

b. The GOES 14 measured electron density reached a maximum of about 8.4x10^{-2} cm^{-3} at about 09:20 UT as Galaxy 15 was exiting eclipse (Figure 3). Peak electron fluxes in the energy range 200-350 keV were about a factor of 4 or 5 higher than the SCATHA "worst case" fluxes[29] of Sept. 22, 1982 that caused numerous discharges on the SCATHA satellite.

c. The GOES 11, 14 and 15 satellites measurements for integral electron fluxes above 0.8 MeV and 2 MeV indicated only a modest increase in the integral electron flux[17]. However, as shown in Figure 4, these fluxes were generally greater at GOES 11 than at GOES 14 or 15. Furthermore, for several minutes following the particle substorm injection observed at GOES 14 at 0902:19 UT, the GOES 11 > 0.8 and > 2 MeV fluxes were similar to the fluxes measured by GOES 14. These measurements suggest that the injected electron spectrum at GOES 11 and at Galaxy 15 was at least as hard as, if not harder than, the spectrum observed at GOES 14. Therefore, it is reasonable to use the GOES 14 measurements as an estimate of the electron spectrum at Galaxy 15.

d. Prior to and at the time of the Galaxy 15 anomaly the measured increases in the proton fluxes measured by GOES 11, 14 and 15 in the solar energetic proton energy range were limited to the 2.5 MeV integral channels (data not shown). While these flux increases were notable it is germane to this discussion that the GOES 11 satellite had previously measured numerous events with higher fluxes over the lifetime of Galaxy 15. During this event, GOES 11, 14 and 15 measured no increase in the > 6.5 MeV and > 11.5 MeV proton energy channels[17]. These factors lead us to believe that the MeV proton flux in the Galaxy 15 environment was not a factor in the anomaly.

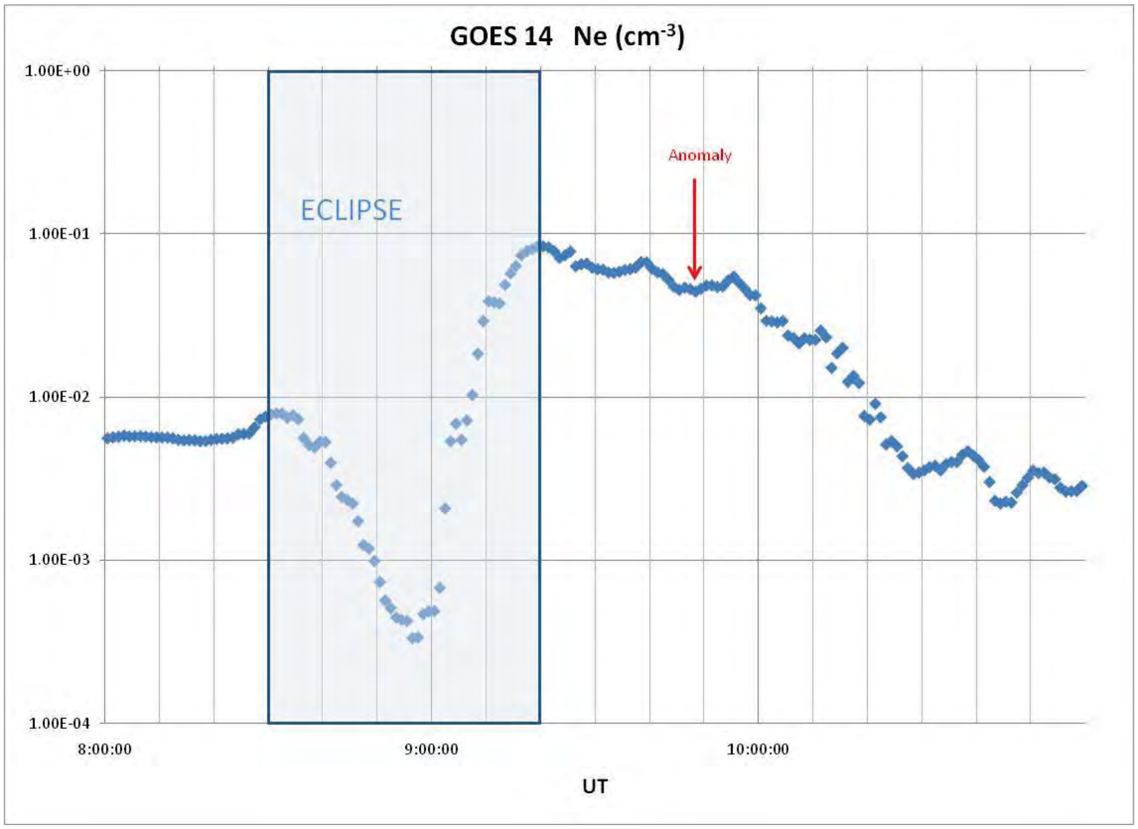


Figure 3. GOES 14 30-600 keV measured electron densities near the time of the anomaly. Eclipse times shown are for Galaxy 15.

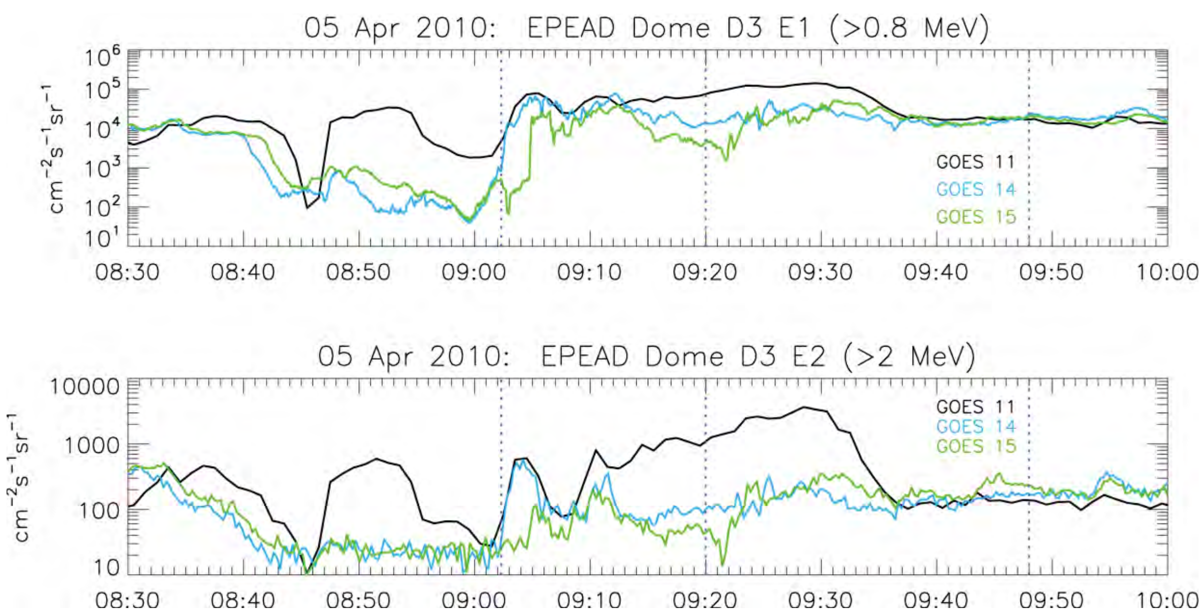


Figure 4. GOES 11, 14 and 15 > 0.8 and > 2 MeV electron fluxes near the time of the anomaly. The GOES 14 and 15 > 2 MeV fluxes were at background levels between 08:42 and 09:02 UT. The vertical dotted lines indicate the UT times of the 30 keV particle injection at GOES 14 (09:02), the Galaxy 15 eclipse exit time (09:20), and the time of the anomaly (09:48).

III. Surface Charging Models of a Generic Galaxy-15-like Spacecraft

NASCAP-2k was used to model the charging of a simulated spacecraft in the measured GEO environment for April 5, 2010. The simplified spacecraft patterned after Galaxy 15 included realistic solar arrays, a spacecraft body, communication dishes, and other relevant features. A materials' view of the model spacecraft for the NASCAP-2k simulation is shown in Figure 5. The back sides of the solar arrays (not shown here) were assumed to be covered in conducting black Kapton®. In order to increase the similarity of the modeled spacecraft to Galaxy 15, the material properties of Teflon® and the Optical Solar Reflector (OSR) were altered to be the same as the black Kapton® and exposed NPaint surfaces were changed to have the properties of aluminum in order to simulate the metallic earth-pointing GPS antennas. A more sophisticated satellite geometry might reveal additional features although for the purposes of this paper this simplified spacecraft model was deemed sufficient.

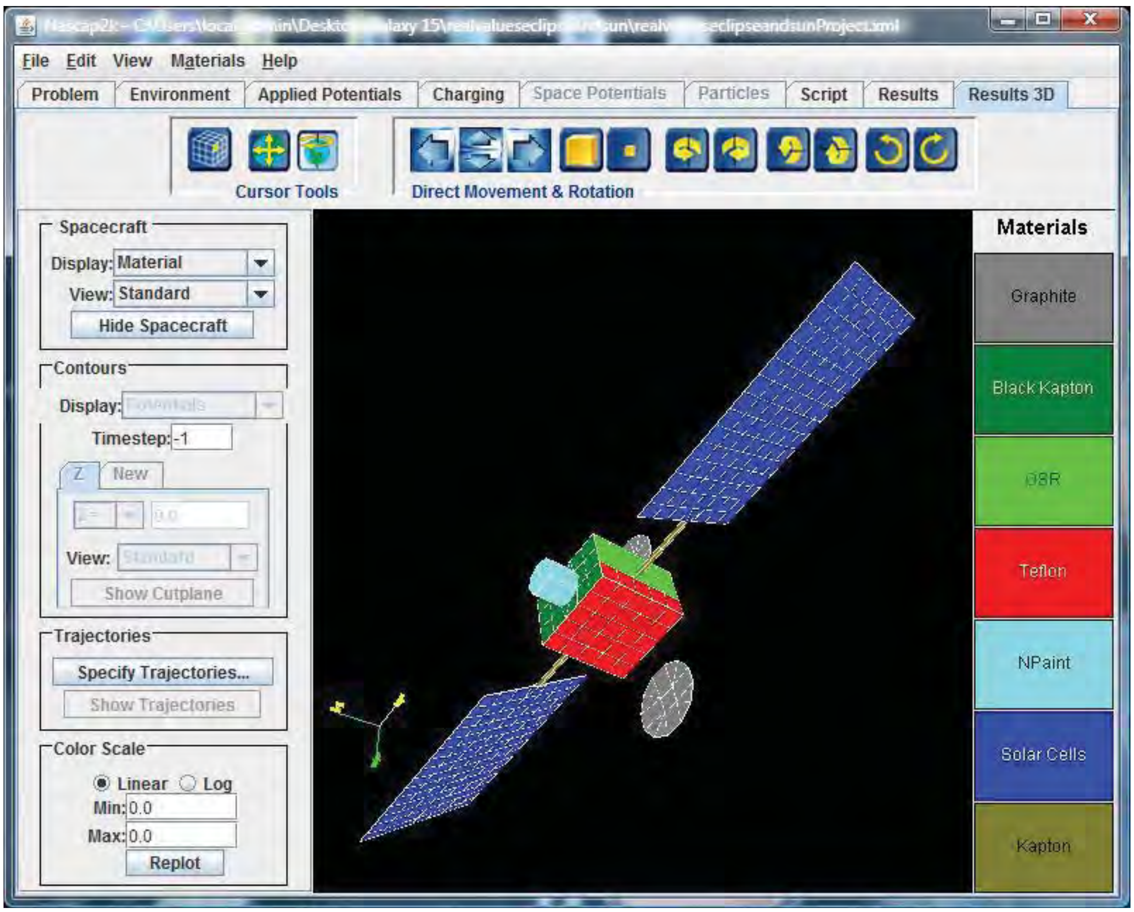


Figure 5. The generic spacecraft modeled by NASCAP-2k.

The potentials reached by the various spacecraft surfaces in the simulation were calculated by placing the spacecraft in a darkened eclipse condition and using the measured GOES 14 space particle environment and magnetic field for 200 seconds, sufficient time for the model to approximately reach steady state. The simulation then continued in a sunlit condition, with conditions seen at the time of the Galaxy 15 anomaly, as the spacecraft exited eclipse. The simulation ended when the spacecraft had been out of eclipse for 28 minutes (as at the time of the Galaxy 15 anomaly). The simulated spacecraft potentials were therefore modeled in two parts representing the eclipse and sunlit periods leading up to the anomaly.

During the eclipse period, the modeled spacecraft reached a potential of -87 kV due to the extremely high electron temperatures present at the peak of the storm. However, the differential potentials across the spacecraft

were only about 1,600 volts, indicating that the charging event was mostly absolute, or bulk, charging. The differential potentials seen at this time may have led to some surface arcing although the NASCAP-2k simulation was only carried out for the last few minutes while the satellite was in eclipse. Overall, we expect that the probability of an ESD in the idealized model conditions was small, because of the short time period for charging. However, it is worth noting that prior to the substorm onset at 09:00 UT the Galaxy 15 electron temperatures shown in Figure 2 were elevated to levels even beyond the NASA worst-case temperature and this environment may have led to differential charging conditions for more that than just a few minutes prior to eclipse exit. Thus, the possibility that surface charging could have led to ESD during the eclipse interval for Galaxy 15 cannot be discounted.

After eclipse, the modeled photoemission was greater than the thermal electron flux to spacecraft surfaces and the extreme negative potentials were found to decrease rapidly to only a few hundred volts negative. As the simulation continued, the differential potentials between spacecraft surfaces built up to a maximum potential of 700 V at the time of the anomaly, due to differences in material photoemission characteristics and shaded versus sunlit surface conditions. Although this maximum differential potential is above the typical threshold level for ungrouted solar-cell arcing in GEO, the differential potentials of the solar cell coverglasses from the structure were only about 100 volts (typically too low for solar-cell plasma arcing to have been initiated). The maximum differential potentials were found at the shadow edges of the solar-panel stalks which, in the modeled spacecraft, were assumed to be covered with non-conductive Kapton®. It is not known whether Galaxy 15 had such non-conducting surfaces or what the actual arc threshold voltage might have been. However if ESD did occur on the solar array or elsewhere due to surface charging, the induced currents would still need to couple into the shielded electronics box (Faraday cage) to cause the observed anomaly.

We conclude from the above that OSC's efforts to cover exposed surfaces of the Galaxy 15 spacecraft with conductive Kapton® make it more unlikely that surface charging, although significant, would have led to ESD as the root cause of the anomaly. Of course, these results are invalid if aging, radiation and/or contamination effects[19] changed the material properties of exposed spacecraft surfaces in the 4½ years Galaxy 15 was on-orbit prior to the anomaly. For this reason, surface charging on Galaxy 15 remains a viable consideration for the anomaly root cause.

Figure 6 shows a NASCAP-2k screen capture of the modeled potentials for the solar-array support structure and the back side of the solar array at the time of the anomaly. Overall, for the reasons mentioned above, the potentials calculated make it unlikely that differential charging would have caused an ESD. However if surface ESDs did occur there is another effect that the conductive coatings could not prevent - the change of structure potential during the ESD. Blowoff currents tend to immediately bring the arc site up to near the plasma potential, which for the case of Galaxy 15 would have suddenly increased the structure potential from -350 volts to near zero.

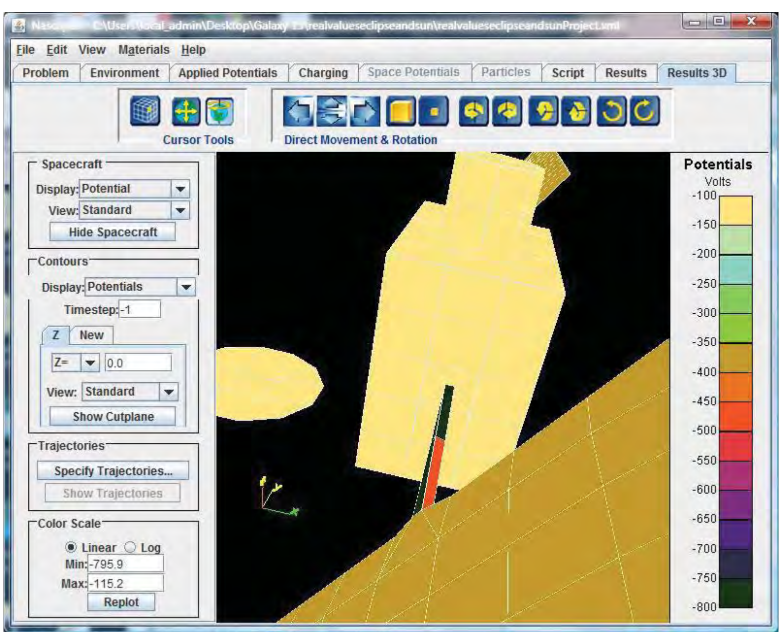


Figure 6. Detailed view of NASCAP-2k calculated surface potentials at the time of the anomaly.

IV. ESTAR, PSTAR and GOES-14 Electron and Proton Fluxes

GOES satellite measurements made at the time of the Galaxy 15 anomaly[17] revealed that the “75-to-475 keV electron flux was the highest observed since GOES 14 was turned on in July 2009 and since GOES 15 was turned on in April 2010,” and that the “GOES 11, 14 and 15 measured increased proton [was] flux limited to the 2.5 MeV channel.” ESTAR and PSTAR[13] Tables of Stopping Power and Range for Electrons and Protons were therefore used to determine the energies of electrons and protons that would be effectively stopped by the MLI and aluminum shielding found on typical satellites. We assume here that the conductive MLI was made of Kapton® with a total thickness 12 mils[20] and that the aluminum thickness for the Faraday cage on Galaxy 15 was 1 mm (per NASA recommendations)[1]. The results indicated that electrons (protons) of > 200 keV (> 5.5 MeV) are required to penetrate 12 mils of Kapton® whereas electrons (protons) of > 600 keV (> 15 MeV) are required to penetrate 1 mm of aluminum. Thus, the observed increased flux of 2.5 MeV protons was presumably insufficient to cause internal charging, but the increased fluxes of mid-range electrons could cause internal charging as they could penetrate the MLI blanket. In addition, neither the electrons nor protons were sufficiently energetic to penetrate the Galaxy 15 Faraday shield.

GOES 14 electron fluxes in the energy channels 200 to 350 keV and 350 to 600 keV were integrated over time from 09:00 UT (start of the substorm) until 09:48 (the anomaly) to determine if the electron fluence could have caused a deep-dielectric discharging in exposed Galaxy 15 materials. The results are intriguing. Electrons of energy > 200 keV had a measured fluence of 7×10^{10} cm^{-2}, squarely in the middle of the range (~1 to 10×10^{10} cm^{-2}) referred to in NASA-HDBK-4002 as the “danger zone” for deep-dielectric discharge. We infer from these results that unshielded and/or ungrounded cables underneath the MLI materials used in the Galaxy 15 design were therefore susceptible to deep-dielectric discharge from energetic electrons in the substorm GEO environment.

We note here that measured electrons in the GEO environment for April 5, 2010 were within the range of electron energies known to produce ESD in Teflon®-coated wiring as determined by tests performed at the Marshall Space Flight Center for the James Webb Space Telescope[3]. While it is true that it is the accumulated electric charge that is important and not necessarily the total fluence of energetic electrons, all that is necessary in the present instance is for these charges to remain embedded within exposed dielectric materials for more than about an hour. This criterion is met by the limited conductivities for many common spacecraft dielectrics.[21] These discharges, if they occurred on Galaxy 15, must have coupled into the system electronics within the spacecraft Faraday cage to have caused the Galaxy 15 anomaly. One possibility is that ESD may have occurred on unshielded wires entering the Faraday cage from the GPS system, if such wires exist.

V. The Case for ESD on Galaxy 15

The cause of the anomaly on Galaxy 15 may remain forever in doubt because the satellite had no instrumentation to determine spacecraft potentials, to measure the local plasma environment or to detect induced arc currents from ESDs. However, there are several strong pieces of circumstantial evidence that make ESD, either from surface charging or deep-dielectric charging, a possibility for the Galaxy 15 anomaly on April 5, 2010. These are:

a. A strong geomagnetic substorm (Kp = 7) hit while Galaxy 15 was in eclipse, immersing the satellite in an elevated flux of high-energy particles,

b. Record high electron temperatures[24] (> 7 times the NASA “worst-case” environment) probably led to extremely high absolute charging levels as suggested by the NASCAP-2k modeling effort,

c. The anomaly occurred shortly after eclipse exit, a time of heightened risk from ESD,

d. The fluence of MLI blanket-penetrating electrons (NIST codes) of energy > 200 keV exceeded the minimum threshold level (NASA-HDBK-4002) for deep dielectric discharging, and

e. Surface differential potentials were probably above the threshold level for plasma arcing.

VI. ESD Possibilities for Anomaly

There are at least three possibilities for ESD involvement with the Galaxy 15 failure:

a. Surface charging – did an arc occur because of surface differential charging? If so, it is likely that the discharge was between some dielectric surface and an adjacent conductor. Our modeling results indicate that a blowoff arc could have changed the structure potential by some 350 volts within microseconds.

b. Deep-dielectric charging – did an arc occur underneath the MLI thermal blankets, perhaps on unshielded or ungrounded wires leading into the electronics otherwise protected by the Faraday cage?

c. Combination – could a change of spacecraft ground potential from a surface charging ESD have triggered a deep-dielectric discharge underneath an MLI blanket? Such so-called sympathetic arcs were found by Vayner et al[22] on anodized aluminum in laboratory simulations of spacecraft charging.

VII. Conclusions and Summary

1) Modeling results indicate that surface and sub-surface charging of spacecraft materials may have exceeded the threshold level for ESD at the time of the Galaxy 15 spacecraft anomaly. This makes ESD a prime candidate at the root cause for the Galaxy 15 anomaly which rendered this spacecraft useless.

   a) The lack of any on-board instrumentation to measure the local environment, determine charging levels or detect the occurrence of ESDs leaves this conclusion unproven. In spite of this uncertainty we offer several recommendations to mitigate the space weather vulnerability of spacecraft in the GEO space environment.

2) Possible corrective design actions for future spacecraft include:

   a. Use accelerated life testing to ensure that EOL (end-of-life) material properties are the same as BOL (beginning-of-life), so that the risks of surface charging can be minimized throughout the spacecraft life,

   b. Allow no unshielded or ungrounded wires or connectors outside of the Faraday cage, including for attached payloads,

   c. Use a Faraday cage made of 0.5 mm aluminum or thicker, similar to the assumed STAR Bus design, to shield sensitive electronics against penetrating electrons,

   d. Employ MLI blankets of sufficient thickness (> 40 mil) to prevent deep-dielectric charging from energetic electrons,

   e. Use grounded conductive surface coatings (with high secondary electron emission and photoemission rates, if possible), even on solar arrays, to prevent differential surface charging, and

   f. Stop flying blind. Include small, lightweight internal charge and/or surface charge monitors in spacecraft designs, as was done with other Intelsat satellites[28], so that hazard warnings can be issued and evaluated in real time, thereby allowing sensitive electronics to be put in safe mode as needed.

Notice: While one of us (Dale Ferguson) signed a non-disclosure agreement with Orbital Sciences Corp., he was never given access to any proprietary material, and no proprietary material was used or reported in this paper.

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